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RESEARCH ARTICLE

Jinyuan SHI, Zhicheng DENG, Yu YANG, Ganwen JUN

Heat transfer coefficient of wheel rim of large capacity steam turbines

Abstract A way of calculating the overall equivalent heat transfer coefficient of wheel rims of large capacity steam turbines is presented. The method and formula to calculate the mean forced convection heat-transfer coefficient of the surface of the blade and for the bottom wall of the blade passage, are introduced. The heat transmission from the blade to the rim was simplified by analogy to heat transmission in the fins. A fin heat transfer model was then used to calculate the equivalent heat transfer coefficient of the blade passage. The overall equivalent heat transfer coefficient of the wheel rim was then calculated using a cylindrical surface model. A practical calculation example was presented. The proposed method helps determine the heat transfer boundary conditions in finite element analyses of temperature and thermal stress fields of steam turbine rotors.

Keywords power and mechanical engineering, steam turbine, rotor, wheel, wheel rim, heat transfer coefficient, calculation formula

1 Introduction

Determining the heat transfer boundary conditions (i.e., calculation formulas for convection heat transfer coefficients) of steam turbine rotor surfaces should be known first when using the finite element method to calculate the temperature fields, the thermal stress fields and the life expectancy of large capacity steam turbine rotors. Known formulas of convection heat transfer coefficient of blade surfaces, smooth rotor surfaces, steam glands, etc,. are based on experimental results and are suitable for engineering practice. Because the structure of wheel rims with inserted blades is complex, calculation method and formulas for the overall equivalent heat transfer coefficient of the wheel rims are still awaiting further research. It is recommended in Ref. [1] that the surface convection heat transfer coefficient of the wheel rims in high pressure stages be 349 W/(m^2·K), those of intermediate pressure stages be 116 W/(m^2·K) and those in low pressure stages be 35 W/(m^2·K). This can only be called an approximation, because it neither considers the discrepancies among convective heat transfer coefficients caused by steam parameter differences among different stages of the same rotor, nor does it consider the differences caused by load variations of the turbine. A method to calculate the heat transfer coefficient of the wheel rims used by a foreign steam turbine company is given in Refs. [2,3], in which $h = 2\lambda_b/(9\pi r_w)$ is recommended to calculate the equivalent convection heat transfer coefficient of the wheel rims, assuming intimate contact between the wheel rims and the blade roots. Here, λ_b is the heat conduction coefficient of the blade material at operating temperature, and r_w is the rim radius. Though the method takes into account the influence of the heat conduction coefficient of the blade material which varies with the operating temperature of the blade, it does not consider the effect of turbine load and steam parameter changes on the overall heat transfer coefficient of the wheel rims, and therefore is an approximate method as well. Because large capacity steam turbines produced in China in the past were exclusively impulse turbines, where the distance between the wheel rim and the life sensitive positions like stress relieving grooves is rather long, the magnitude of approximated equivalent heat transfer coefficients of the wheel rims may exert but a small influence on the calculation results of the temperature fields, the thermal stress fields and the life span of turbine rotors. However, the 300 MW and 600 MW steam turbines presently manufactured in China and the imported steam turbines produced by such companies as Siemens, Westinghouse, ABB, Alsthom, and Mitsubishi Heavy Industries in other countries are all of the reaction type. Since in reaction the turbine blades are mounted on the circumferential surface of the rotor drums, the calculated magnitudes of overall heat transfer coefficient

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Jinyuan SHI (✉), Zhicheng DENG, Yu YANG, Ganwen JUN
Shanghai Power Equipment Research Institute, Shanghai 200240, China
E-mail: shijinyuan@speri.com.cn

directly affect the calculation accuracy of the temperature fields, the thermal stress fields and the life consumption of rotors. For engineering purposes, a simple and practical formula is needed to calculate the overall equivalent heat transfer coefficient of the wheel rims of large capacity steam turbines. The research on practical formula to calculate the heat transfer coefficient of the wheel rims is, therefore, a utilitarian work.

2 Equivalent heat transfer coefficient of blade passages of steam turbines

2.1 Calculation formula of the mean convection heat-transfer coefficient of blade surfaces

A formula of the mean forced convection heat-transfer coefficient of blade surface obtained by tests is given in Ref. [4]:

$$h_b = \frac{K_1\left(1+0.8Su^{0.42}\right)Re^{0.66}\lambda Pr}{b_2 Sr^{0.58}}, \tag{1}$$

where, K_1 is a test obtained constant; Re is the Reynold's number; λ is the heat conduction coefficient of the steam; Pr is the Prandel's number and b_2 is the chord length of the blade.

$$Su = \frac{u_m \cdot H_b}{v_2 \cdot d_m}, \tag{2}$$

where, u_m is the circumferential velocity at the mean diameter, H_b is the height of the blade, v_2 is the relative velocity at blade outlet and d_m is the mean diameter of the stage.

$$Sr = \frac{\sin\beta_1}{\sin\beta_2}\left[\frac{2B_b}{t_2\sin(\beta_1+\beta_2)\cos^2\left(\frac{\beta_1-\beta_2}{2}\right)}-1\right]^{1/2}, \tag{3}$$

where, β_1 is the incidence of the moving blade and β_2 the outflow angle, B_b is the axial width of the blade and t_2 is the pitch of cascade.

2.2 Calculation formula for the convection heat transfer coefficient of the bottom wall of the blade passage

According to Ref. [4], a formula for forced convection heat transfer coefficient of the bottom wall of the blade passage is given by

$$h_p = \frac{K_2\left(1+1.1Su^{0.59}\right)\left(1+0.7Sr^{-0.54}\right)Re^{0.8}Pr^{0.43}\lambda}{b_2}, \tag{4}$$

where, K_2 is a test obtained constant.

2.3 Calculation formula for the equivalent heat transfer coefficient of the blade passage

Heat transmission from the blade to the rim is simplified by the analogy of heat transmission in the fins. Assume that the convection heat transmission at the blade tips can be neglected, then according to Refs. [5–10] the heat Φ_1 transmitted from the profiled blade to its bottom can be calculated by making use of a heat transmission model of fins:

$$\Phi_1 = \Delta t_1(h_b\lambda_b P F_1)^{1/2}\,\mathrm{th}\left[H_b\left(\frac{h_b P}{\lambda_b F_1}\right)^{1/2}\right], \tag{5}$$

where, Δt_1 is the difference between metal temperature at the bottom of the profiled blade and the steam temperature, h_b is the mean convection heat transfer coefficient of the surface of the blade, λ_b is the heat conduction coefficient of the blade material, F_1 is the cross-sectional area at the bottom of the profiled blade, and P is the circumferential length of this section, H_b is the height of the blade, and the hyperbolical function that stands for th x is th $x = (e^x - e^{-x})/(e^x + e^{-x})$.

The total heat transfer rate Φ from the whole blade passage to the wheel is composed of the convective heat transfer rate $z\Phi_1$ where z is the number of blades, $z\Phi_1$, and the heat transfer rate from steam to the bottom wall of the blade passage, Φ_2, thus

$$\Phi = z\Phi_1 + \Phi_2 = z\Phi_1 + h_p F_2 \Delta t_2 = h_e F_3 \Delta t_3, \tag{6}$$

where, h_p is the convection heat transfer coefficient of the bottom wall of the blade passage; h_e is the equivalent heat transfer coefficient of the blade passage; Δt_2 is the temperature difference between the bottom wall of the blade passage and the steam; $\Delta t_3 = (\Delta t_1 + \Delta t_2)/2$ is the difference between the steam temperature and the mean surface temperature of the bottom of the profiled blade passage; F_2 is the area of the bottom wall of all blade passages in total, $F_2 = 2\pi B_b r_b - zF_1$, where B_b is the axial width of the blade, r_b is the radius of the bottom wall of the blade passage, $F_3 = zF_1 + F_2 = 2\pi B_b r_b$.

Stringently speaking, Δt_1, Δt_2 and Δt_3 are not the same, but in engineering practice they can be regarded as approximately the same herewith:

$$h_e = \frac{z}{2\pi B_b r_b}\left\{(h_b\lambda_b P F_1)^{1/2}\,\mathrm{th}\left[H_b\left(\frac{h_b P}{\lambda_b F_1}\right)^{1/2}\right] + \frac{h_p}{z}(2\pi B_b r_b - ZF_1)\right\}. \tag{7}$$

Generally, $H_b\left(\frac{h_b P}{\lambda_b F_1}\right) > 3$, wherewith $\mathrm{th}\left[H_b\left(\frac{h_b P}{\lambda_b F_1}\right)^{1/2}\right] \approx 1$, and we get approximately

$$h_e = \frac{z}{2\pi B_b r_b}\left[(h_b \lambda_b P F_1)^{1/2} + \frac{h_p}{z}(2\pi B_b r_b - z F_1)\right]. \tag{8}$$

3 Method to calculate the overall equivalent heat transfer coefficient of wheel rims

Blades are inserted in the blade root grooves of the rotor ace. All the wheel rims are covered with blades. The convection heat from the flowing steam enters the surface of the blades and the bottom wall of blade passages. It is then conducted into the wheel rims via the blade roots. Thermal contact resistance exists between the blade root and the wheel rim. The wheel rims are generally simplified and substituted by mechanical models used for finite element calculation analysis of the temperature fields and thermal stress fields. It is assumed that the thermal conductivity of the blade roots and wheel rims is the same, and that the blade roots, installed in the wheel grooves to be an integral part of the wheel rim. Thus, an axisymmetric mechanical model may be used. The heat transfer boundary condition at the outer radius (i.e. rim radius r_w) is treated as a third type boundary for calculating the convective heat transfer from steam. The overall heat transfer coefficient k of the wheel rim is then calculated using a cylindrical model. The outer radius r_b is that of the bottom wall of the blade passage, the inner radius is the same as the outside radius of the wheel rim r_w, and the axial width of the cylinder is equal to the axial width of the blade B_b. The thermal resistance to heat transmission to and through the cylindrical wall is composed of the following two parts.

(1) The thermal resistance to heat transfer at the outer surface of the cylindrical wall

$$R_1 = \frac{1}{2\pi r_b B_b h_e}. \tag{9}$$

(2) The thermal resistance to heat conduction through the cylindrical wall without considering the contact resistance of the blade root

$$R_{20} = \frac{1}{2\pi B_b \lambda_b} \ln \frac{r_b}{r_w}. \tag{10}$$

(3) After taking contact resistance between the blade root and the wheel rim into consideration, the thermal resistance to heat conduction across the cylinder wall increases. The actual thermal resistance to heat conduction across the cylindrical wall can be represented by

$$R_2 = K_3 R_{20} = \frac{1}{2\pi B_b \lambda_b} K_3 \ln \frac{r_b}{r_w}. \tag{11}$$

where K_3 is an experimental constant.

According to the principle of addition of thermal resistances in series, the overall thermal resistance of the cylinder wall is given by

$$R = R_1 + R_2 = \frac{1}{2\pi r_b B_b h_e} + \frac{1}{2\pi B_b \lambda_b} K_3 \ln \frac{r_b}{r_w}. \tag{12}$$

The axial width B_w of the wheel rims are generally not the same as those of the blades' B_b. The formula to calculate the overall heat transfer coefficient k referred to the internal area of the cylinder wall (i.e., the external surface area of the wheel rim $F = 2\pi r_w B_w$) can then be expressed by

$$k = \frac{1}{FR} = \frac{1}{2\pi r_w B_w R} = \left[\frac{r_w B_w}{r_b B_b h_e} + \frac{r_w B_w}{B_b \lambda_b} K_3 \ln \frac{r_b}{r_w}\right]^{-1}. \tag{13}$$

4 Practical example

The governing stage of a certain 600-MW steam turbine uses impulse type blades while the remaining stages of the high and the intermediate pressure rotor use reaction blades. The calculated overall heat transfer coefficient of the governing stage of the wheel rim, that of the high pressure rotor, that of the last stage, and that of the first and last stage of intermediate pressure rotor are given in Table 1. To compare with existing methods, the calculation results, with those given in Refs. [1–3] are also listed in Table 1.

By analyzing the data listed in Table 1 and the methods used, the following opinions can be deduced.

(1) According to Ref. [2] the formula $h = 2\lambda_b/(9\pi r_w)$ to calculate the convection heat transfer coefficient of the wheel rim is used by Westinghouse Electric Company. The origin or the deduction process of the formula is unknown. Since h and h_b/r_0 are directly proportional to one another, there may exist a certain relationship between h and the heat conductivity of the cylindrical wall. Assuming that there is close contact between the blade root and the wheel (neglecting contact resistance), the formula to calculate the heat transfer coefficient of the heat conduction of the cylindrical wall becomes $h = \lambda_b/[r_w \ln(r_b/r_w)]$. Comparing these two formulas, it is possible that in demising the formula given in Ref. [2] ln (r_b/r_w) has been approximated by 4.5π. This approximation treatment may fit some specific construction, but it is not generally suitable. The main shortcoming of the calculation given in Refs. [2,3] is that the forced convection heat transfer from the steam to the surface of the blade and the bottom wall of the blade passage are not considered which makes the calculated values of the equivalent heat transfer coefficient of the wheel rims too small.

Table 1 Calculated equivalent heat transfer coefficients of a steam turbine wheel rim

operating conditions assumed for calculation	type of blade root	by the method in [1]/ $W \cdot m^{-2} \cdot K^{-1}$	by the method in [2,3]*/ $W \cdot m^{-2} \cdot K^{-1}$	by the method** in this paper/$W \cdot m^{-2} \cdot K^{-1}$
governing stage at 100% load	fork type	349	3.34	1063
governing stage's at 50% load	fork type	349	3.24	1023
HP last stage at 100% load	inverted-t-type	349	3.91	469
HP last stage at 50% load	inverted-t-type	349	3.85	451
IP first stage at 100% load	fir-tree-type	116	3.46	2391
IP first stage at 50% load	fir-tree-type	116	3.46	2065
IP last stage at 100% load	fir-tree-type	116	3.38	2232
IP last stage at 50% load	fir-tree-type	116	3.39	1789

Notes: * The quantitative order of the calculated results are the same as those given in Ref. [3]; ** The reason why the overall equivalent heat transfer coefficients of the wheel rim of HP rotor is smaller lies in the fact that contact resistance of fork type blade roots and inverted-T-type blade roots are both large.

(2) That the convection heat transfer coefficients of the wheel rim is taken as constant in Ref. [2] may perhaps have originated from the calculated results obtained under some operational conditions for some special kind of blade root construction of some special stage, which cannot be considered generally applicable.

(3) The calculation formula of the equivalent heat transfer coefficient for blade passages as given in this paper takes into consideration both considered forced convection heat transfer from the steam to the surface of the blade, and to the bottom wall of the blade passage. The calculation formulas for convection heat transfer coefficients of the surface of the blade and the bottom wall of the blade passage are the empirical formulas suggested by Russia engineers, and are based on experimental test results.

(4) A fin heat transfer model is used to calculate the equivalent heat transfer coefficient of the blade, and a cylindrical wall model is used to calculate the overall heat transfer coefficient of the wheel rim. These mathematical models are simple and their physical meaning is clear.

(5) The proposed method in this paper takes into consideration forced convection heat transfer from the steam to the surface of the blade and that from the steam to the bottom wall of the blade passage. Moreover, the influence of contact resistance between the blade root and the wheel rim as well as the effect of steam parameter variations at different loads are also taken into account. Thus, the problem is being treated in a more comprehensive way.

5 Conclusions

1) The method proposed in this paper to calculate the equivalent heat transfer coefficient of the wheel rims of large capacity steam turbines is feasible for engineering purposes. By taking into consideration the forced convection heat transfer from the steam to both the surface of the blade and the bottom wall of the blade passage (together with the heat conduction across the blade roots, the contact resistance between the blade root and wheel rim as well as steam parameter variations within the blade passage under different load and conditions), the problem is being treated in a more comprehensive way.

2) The proposed method to calculate the equivalent overall heat transfer coefficient of the wheel rims of large capacity steam turbine rotors may also be applied to obtaining the equivalent overall heat transfer coefficient at different positions of a wheel rim with different blade root structures and under different load conditions, thus providing heat transfer boundary conditions for finite element calculation of temperature fields and thermal stress fields, and herewith a scientific basis for life design, life assessment and life management of steam turbine rotors. The method given in this paper may also principally be used to calculate the equivalent overall heat transfer coefficients of wheel rims of gas turbine rotors, aero-engine rotors and axial flow compressor rotors.

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